ANALYSIS OF THE SEVERE ACCIDENT PROGRESS IN AP1000 REACTOR VESSEL UNDER FLOODED CAVITY CONDITION

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Abstract: In-Vessel Retention (IVR) through External Reactor Vessel Cooling (ERVC) has been becoming a potential severe accident management strategy. It has been performed by flooding cavity with water, so reactor vessel will be submerged and cooled from outside. The cooling process by nucleate boiling is expected, therefore the integrity of reactor vessel will be sustained. AP1000 is an advanced pressurized water reactor which has been adapted IVR as a severe accident management strategy.

This paper will analyze AP1000 in-vessel severe accident progress under flooded cavity condition by using MELCOR1.8.6 code. The analyzed - scenario here is one of the most conservative scenarios that is loss of coolant accident (LOCA) caused by the cold leg end-double rupture (Large Break LOCA) which simultaneously happens with total station blackout (SBO). Beside, the short term reactor core cooling is assumed to be available whereas the long term reactor core cooling is unavailable. These assumption aim to increase the conservation of the scenario.

The work done in the paper is the first step in the long term IVR-ERVC study with efforts to combine MELCOR code with PECM (Phase-changed Effective Convectivity Model). The results showed that under the accident scenario with only the availability of short term reactor core cooling system and flooded cavity could not prevent lower head from failure due to thermal creep.

Key words: *AP1000, IVR, MELCOR1.8.6, severe accident.*

I. INTRODUCTION

In-Vessel Retention through External Reactor Vessel Cooling was proposed and studied by T.G. Theofanous and his colleagues **[1]**, and was firstly adapted as a severe accident management strategy for Loviisa nuclear power plant (Finland) **[2]**. But it was firstly completely studied for AP600, the results showed that under any scenarios with requisite conditions for IVR such as depressurizing reactor coolant system, flooding cavity, no penetration from lower head, forming ventilation channel between reactor vessel and isolation panel were met, the lower failure by thermal load was *physically unreasonable* **[3]**.

Thank to successful adaption IVR for AP600, the idea for adapting IVR for higher power reactor came up. So far, there are many studies which have been done preliminarily for higher power reactor, such as ULPU Configuration V experiment concluded that *the In-Vessel Retention idea was extendable to higher power reactors such as AP1000* **[4]**; studying critical heat flux and preliminary study of IVR-ERVC for APR1400 **[5]**; using MELCOR1.8.6 to simulate In-Vessel Retention strategy for VVER1000/320, firstly analyzed results predicted successful cooling of the reactor pressure vessel for sufficiently long period **[6]**, or even studying IVR-ERVC phenomena for large scale pressurized water reactor, a three-loop 5000MWt reactor, by coupling analysis in- and ex-vessel severe accident progress **[7]**.

The preliminary results indicate the potential adaption of IVR-ERVC for higher power reactor, even there are many uncertainties, such as in-vessel severe accident progress determines the configuration of molten pool in lower plenum; the stratification and multi components affect heat transfer in molten pool and molten pool with lower head vessel; or external cooling ambient... One of the solutions to reduce the uncertainties is the combination between severe accident analysis codes, likely SCDAP/RELAP5, MELCOR, with mechanic-thermal interaction analysis codes likely CFD (FLUENT), ASTEC, PECM, such as the combination between MELCOR code with PECM which has been performing at Institute for Nuclear and Energy Technologies **[8]**.

The work done in this paper is the first step in the long term IVR-ERVC study with efforts to combine MELCOR code with PECM. The MELCOR 1.8.6 version will be chosen to study in-vessel severe accident progress in the paper. MELCOR 1.8.6 has some new features to improve the capability of simulating and calculating severe accident in light water recactor, especially are the improvements in molten pool model in lower head and new nodalization model for lower head vessel which improve the capability of calculating heat transfer between molten pool with lower head vessel, and between lower head vessel with external cooling ambient **[9]**.

In the paper, the analyzed scenario is the Large Break LOCA (LBLOCA) simultaneously happens with the station blackout (SBO) accident, in order to increase the conservation of the scenario the short term core cooling systems, including CMTs and ACCs, will be assumed to be available whereas the long term cooling from IRWST is unavailable. Because of large break loss of coolant accident, therefore the PRHR-HX and ADS will be ignored. The LBLOCA is initiated by cold leg double ended-rupture with the break diameter size of 558.8 mm on the second loop in which the pressurizer is connected.

II. AP1000 PASSIVE SAFETY SYSTEMS

The AP1000 nuclear power plant is an advanced pressurized water reactor design developed by Westinghouse. Its outstanding features are passive safety systems which operation will be governed by the natural principles such as gravitation and natural circulation. They are automatic depressurization system (ADS), the short term core cooling systems including core makeup tanks (CMTs) and accumulators (ACC), the long term core cooling system including in-containment refueling water storage tank (IRWST), passive heat removal system (PHRS), in-vessel retention (IVR) …, are aimed to protect nuclear power plant safely under severe accident conditions without intervention of operators.

In this case, only the short term core cooling systems (CMTs and ACCs) and the severe accident management strategy IVR are involved, other passive safety systems will be ignored. Therefore the following, the paper only discusses about the short term core cooling systems and IVR **[10]**:

The core makeup tank system (CMTs) consists of two cylindrical tanks (Fig.1). Each tank will be fully filled by 70.792116 m^3 of borated water at 343^oK. Tanks bottom are directly connected to reactor vessel through direct vessel injection in order to inject water into reactor vessel directly under gravitation, top of them are connected to cold leg by a line, so called balance line. CMTs have the role to supply water into reactor vessel in case there is an accident which leads reactor core loss water at high pressure (12.71 MPa).

The accumulators (ACCs) consist of two spherical tanks (Fig.1) which contain borated water at 320^oK and are compressed by nitrogen gas at pressure 4.9 MPa. Volume of a tank is 56.6 m^3 in which water occupies 48.14 m^3. Accumulators bottom are connected to direct vessel injection line, borated water will be injected directly to reactor vessel when pressure in reactor coolant system decreases below 4.9 MPa.

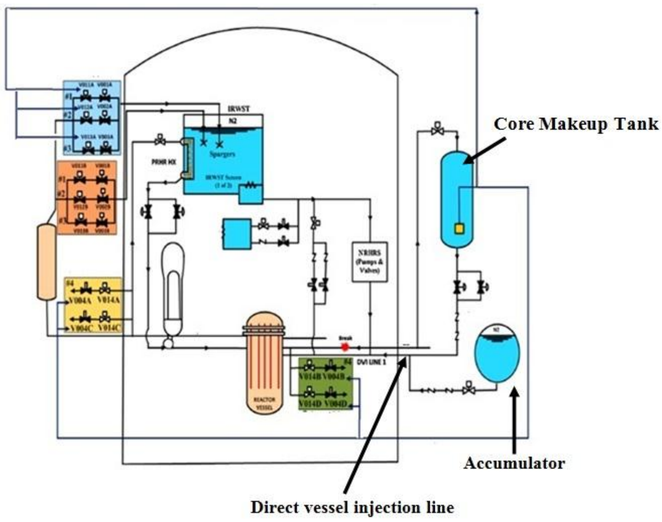


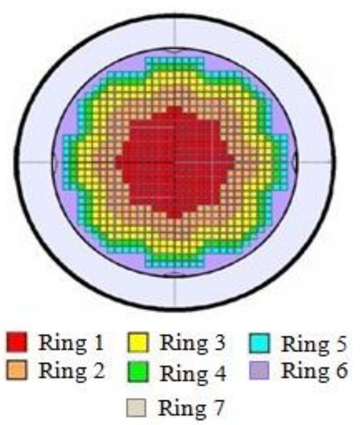
Fig 1: The passive safety systems of AP1000 [10].

The in-vessel retention (IVR) is a unique severe accident management strategy of AP1000 nuclear power plant technology. With the specific cavity geometry and two-phase ventilation channel formation between insulation frame and reactor vessel facilitate IVR-ERVC. In case of accident, the

IVR will be performed by flooding cavity with water from IRWST and condensed water from inside of primary containment vessel when steam’s temperature in reactor coolant system exceeds 650°C. The heat exchange between lower head and water in channel is expected to be nucleate boiling which is the best heat removal in order to prevent lower head from thermal crisis, therefore the integrity of lower head will be preserved.

III. AP1000 NODALIZATION IN MELCOR

The reactor core and lower plenum were divided into 7 concentric radial rings and 14 axial levels (Fig.3). In seven concentric radial rings, the first five rings is for reactor core and the sixth ring is for bypass area which is gap between core shroud and core baffle, the last ring is for downcomer (new feature of MELCOR 1.8.6 can model the downcomer area as a core ring). In fourteen axial levels, the first five levels is in lower plenum, the sixth level is for lower core support plate, and the remain rings is in reactor core.



	Ring 1	2	3	4	5	6	7	
14	114	214	314	414	514	614	714	Upper core support plate
13	113	213	313	413	513	613	713	Core
12	112	212	312	412	512	612	712	Core
11	111	211	311	411	511	611	711	Core
10	110	210	310	410	510	610	710	Core
9	109	209	309	409	509	609	709	Core
8	108	208	308	408	508	608	708	Core
7	107	207	307	407	507	607	707	Core
6	106	206	306	406	506	606	706	Lower core support plat
5	105	205	305	405	505	605	705	Lower plenum
4	104	204	304	404	504	604	704	Lower plenum
3	103	203	303	403	503	603	703	Lower plenum
2	102	202	302	402	502	602	702	Lower plenum
Level 1	101	201	301	401	501	601	701	Lower plenum

Figure 2: MELCOR modeling for reactor core and lower plenum.

The liquid volume inside reactor vessel, four cold legs, two hot legs, pressurizer and surge line, two core makeup tanks and two accumulators were modeled as control volumes, the connections between these volumes were modeled as flow paths (Fig.3). Especially the direct vessel injection lines were modeled as control volumes in order to see the mutual effects between core makeup tank and accumulator (Fig.3). The lower head vessel was divided into 6 layers and 9 segments (Fig.4). The cavity, water resource for flooding cavity, and the gap (channel) between reactor vessel and insulation frame are modeled as control volumes (Fig.5). All connections and ventilating orifice were modeled as flow paths (Fig.5).

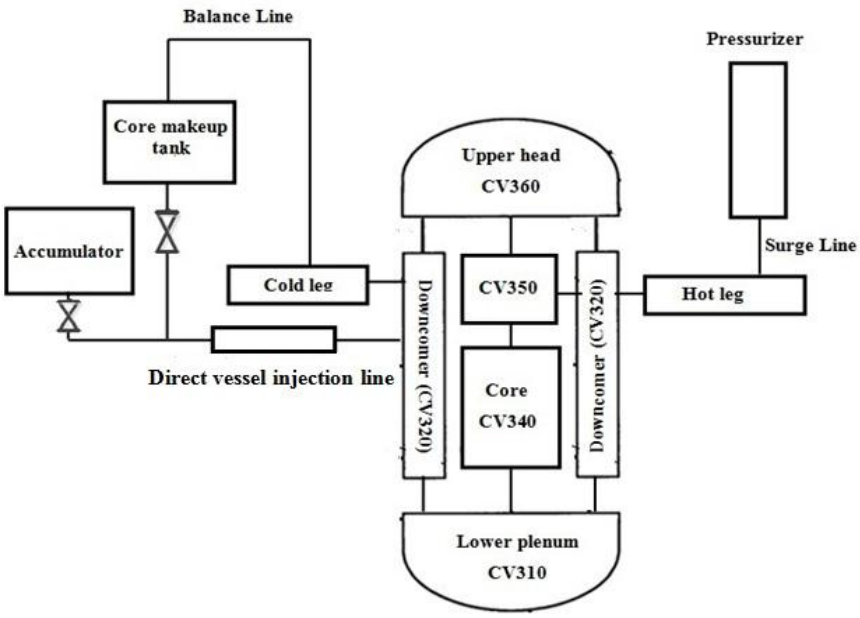


Figure 3: Nodalization scheme of reactor core coolant system and passive core cooling systems.

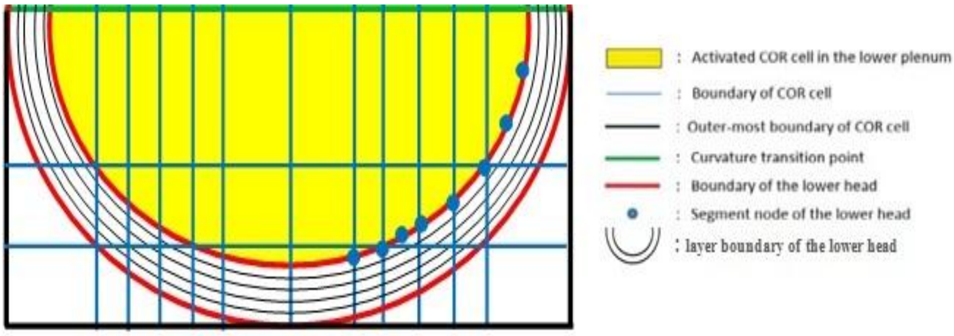


Figure 4: Nodalization scheme of lower head vessel.

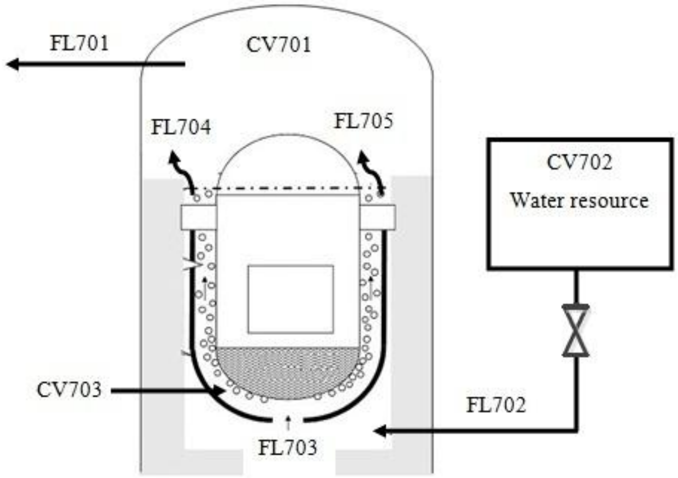


Figure 5: The nodalization scheme of cavity and water resource.

According to the design of AP1000, IRWST is the main water resource which provides and sustains the water level in cavity for IVR strategy. In case of LOCA, condensed water on the inside of the primary containment will be also drain to flood cavity. However, in this work, there is no simulation for condensed water and the IRWST is assumed to be failure. Therefore, an unlimited water resource will be modeled instead. The water temperature in the water resource is 47^{o}C (323^{o}K), water was injected to cavity to submerge reactor vessel up to height of cold leg when steam temperature in reactor vessel exceeds 650^{o}C (923^{o}K).

IV. MOLTEN POOL HEAT TRANSFER MODELS IN MELCOR 1.8.6

MELCOR1.8.6 has a lot of improvements in modeling the molten pool. It can simulate the formation of molten pool in reactor core and lower plenum as well (Fig. 6) , and the stratification of molten pool. Especially, the ability of simulating the stratification of molten pool in lower plenum significantly improve the calculation of heat transfer between molten pool and lower head vessel.

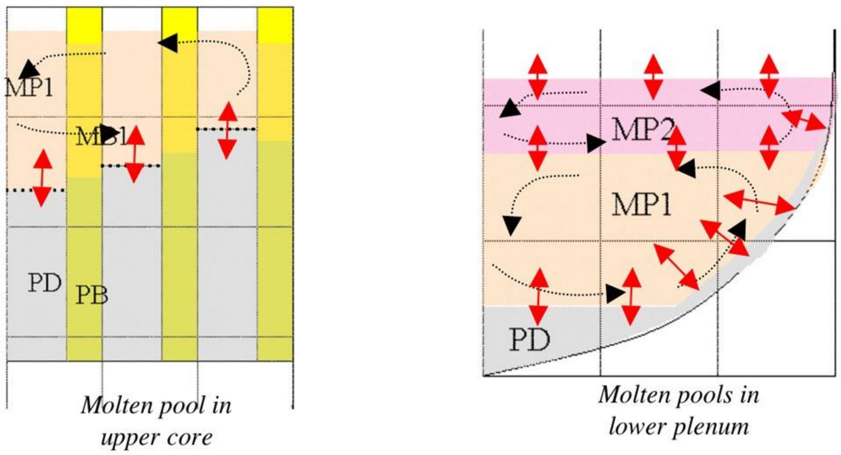


Figure 6: Molten pools in MELCOR 1.8.6 [9].

The heat transfer of molten pool are characterized by the Nusselt correlation [9]:

$$Nu = A(j)Ra^{n(j)}Pr^{m(j)} \tag{4.1}$$

Where: Nu is the Nusselt number; Ra is the Rayleigh number; Pr is the Prantl number; A(j), n(j), m(j) are sensitivity coefficients; j is the algebraic number. They are summarized in Table 4.1:

Table 4.1: Assumed convective boundary condition at molten pool surfaces [9]

j	Description	Rayleigh number	A(j)	n(j)	m(j)
1	Oxide pool to radial boundary	Internal	0.3	0.22	0
2	Oxide pool to interface	Internal	0.381	0.234	0
3	Oxide pool to atmosphere	Internal	0.381	0.234	0
4	Metallic pool to lower surface	External	0.69	0.333	0.074
5	Metallic pool to radial surface	External	0.3	0.22	0
6	Metallic pool to upper surface	External	0.3	0.22	0

V. HEAT TRANSFER MODEL OF LOWER HEAD VESSEL

Heat transfer model of lower head vessel has been significantly improved in MELCORE 1.8.6 compared to previous version. It can not only simulate and calculate the through-wall in each segment but also the transverse heat transfer between segments. Figure 7 demonstrated nodalization of a segment and heat transfer process.

Transverse heat transfer [9]:

$$q_{(i,j)\to(i,j+1)} = \frac{1}{\frac{\tau_j}{k_{i,j}}+\frac{\tau_{j+1}}{k_{i,j+1}}} A_{transverse,j}\left(T_{h(i,j)} - T_{h(i,j+1)}\right) \tag{5.1}$$

Through-wall heat transfer [9]:

$$q_{(i,j)\to(i+1,j)} = k_{i,j} FAC\ A_h \frac{T_{h(i,j)} - T_{h(i+1,j)}}{\Delta Z_i} \tag{5.2}$$

Where:

$q_{(i,j)\to(i+1,j)}$ = horizontally heat transfer rate from node (i,j) to node (i+1,j),

$q_{(i,j)\to(i,j+1)}$ = vertically heat transfer rate from node (i,j) to node (i,j+1),

$k_{i,j}$ = thermal conductivity of node (i,j),

$T_{h(i,j)}$ = temperature of lower head node (i,j)

ΔZ_i = width of mesh layer i,

τ_j = transverse path length of from center of node (i,j) to boundary,

A = heat transfer area.

In MELCOR 1.8.6, the outer boundary of lower head can transfer heat to multiple volumes that makeup the reactor cavity. Heat transfer calculation between each segment and ambient, as follows [9]:

$$q_{h,c} = h_{ATM}(1 - F_{PL})A_h\left(T_{h_1} - T_{ATM}\right) + h_{rlx,PL}F_{PL}A_h(T_{h,1} - T_{SAT}) \tag{5.3}$$

Where:

h_{ATM} = heat transfer coefficient from lower head to reactor cavity atmosphere,

$h_{rlx,PL}$ = relaxed heat transfer coefficient from lower to reactor cavity pool,

F_{PL} = pool fraction of surface area A_h,

T_{ATM} = temperature of reactor cavity atmosphere,

T_{SAT} = saturation temperature of reactor cavity pool

$T_{h,1}$ = lower head outer surface temperature at the beginning of the time step.

And the critical heat flux will be estimated as follow [9]:

$$q_{CHF}(\theta) = (0.034 + 0.0037\theta^{0.656})\rho_v^{1/2} h_{lv}[g\sigma(\rho_l - \rho_v)]^{1/4} \tag{5.4}$$

Where:

θ = inclination angle of the surface in degrees,

ρ_l, ρ_v = densities of water and steam, respectively,

g = acceleration of gravity,

σ = interfacial surface tension between steam and water,

h_{lv} = latent heat of vaporization of water.

The failure of lower head vessel will occur when the creep-rupture failure of a lower head segment occurs. The creep-rupture failure model uses the temperature profile through lower head to calculate creep based on a Larson-Miller parameter and a life-fraction rule [9].

The Larson-Miller creep-rupture failure model gives the time to rupture, t_R, in seconds, as [9]:

$$t_R = 10^{\left(\frac{P_{LM}}{T} - 7.042\right)} \tag{5.5}$$

Where: T is the temperature of segment and P_{LM} is the Larson-Miller parameter given by:

$$P_{LM} = 4.812 \times 10^4 - 4.725 \times 10^3 \log_{10} \sigma_e \tag{5.6}$$

The life-fraction rule gives the cumulative damage, expressed as plastic strain, $\varepsilon_{pl}(t)$, as:

$$\varepsilon_{pl}(t + \Delta t) = \varepsilon_{pl}(t) + 0.18\frac{\Delta t}{t_R} \tag{5.7}$$

The failure occurs when the strain reaches 18%.

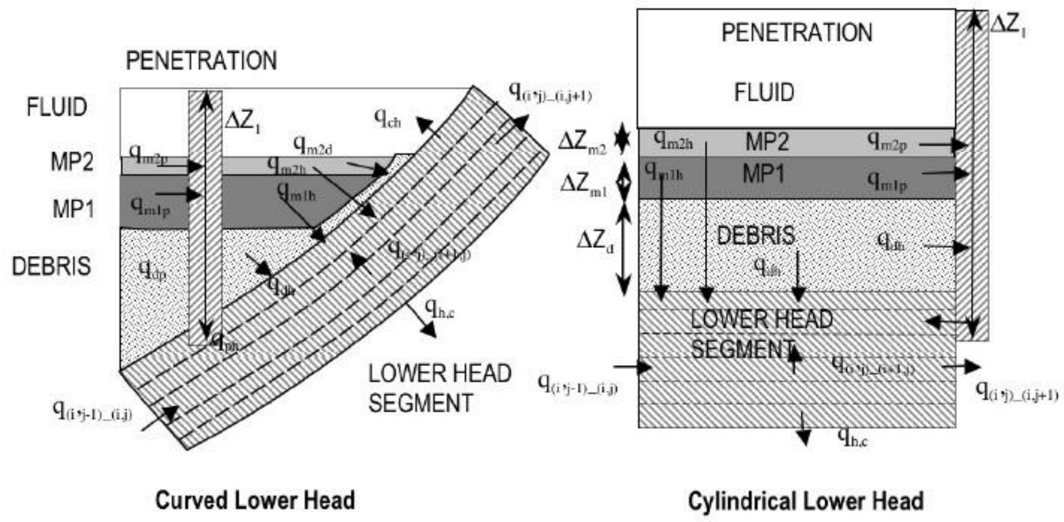


Figure 7: Configuration and heat transfer scheme of a segment [9]

VI. RESULTS AND DICCUSSION

The accident occurs at 0.0 second. Due to large break, pressure in reactor vessel drops quickly led the reactor trip signal is generated immediately after 0.2 second, and due to SBO all active safety systems are unavailable. The following is chronology of the events in MELCOR analysis:

Time	Event
0.0 s	Occurrence of LBLOCA and SBO
0.2 s	Reactor trip
0.637 s	Actuation of CMTs
11.840 s	Actuation of ACCs
63.0 s	Start of oxidation
360.102 s	Actuation of flooding cavity
400 s	ACCs were empty
580.0 s	Start of fuel cladding failure
750.0s	Presence of debris in lower plenum
800 s	CMTs were empty
3318.13 s	Failure of core support plate by yielding led mass relocation of debris to lower plenum
19937.3 s	Lower head vessel failure

Accident progress in reactor core and response of passive core cooling systems

Because of large break, pressure in reactor coolant system (RCS) quickly drop equal to pressure of containment (Fig.8) and almost water in RCS was ejected to containment (Fig.9). After 10 seconds, reactor core totally lost water and then partially recovered due to the water injection from CMTs and ACCs (Fig.10).

The CMTs were actuated at 0.637s whereas ACCs were actuated at 11.840s when pressure in core reached to theirs set points (Fig.9). The mutual effect in mass flow rate between CMTs and ACCs was demonstrated by Fig 11. After 90s from actuation, due to the decrease of water level of CMTs, it led theirs mass flow rate to be smaller than that of ACCs, therefore mass flow rate of CMTs were dominated by that of ACCs and dropped to zero. But at 190s, mass flow rate of CMTs started to recover due to the decrease of mass flow of ACCs.

After reactor was tripped, reactor core continued to heat up by heat from fission products decay (Fig 12). Due to quick loss of water through the large break, even water was additionally supplied from CMTs and ACCs but the supplement only partially recovered reactor core, this led the temperature of upper core area kept increasing. Under the high temperature condition and presence of steam in reactor core is favourable condition for core structure oxidation, the oxidation began at 63.0s and total mass of hydro generated in core were 308kg (Fig 13). The core was intensively heated by heat from heat-generating oxidations (Fig 14), the cladding temperature promptly increased to melting point of Zircaloy cladding, the cladding temperature and degradation of cladding in ring 1 was shown in Figure 15.

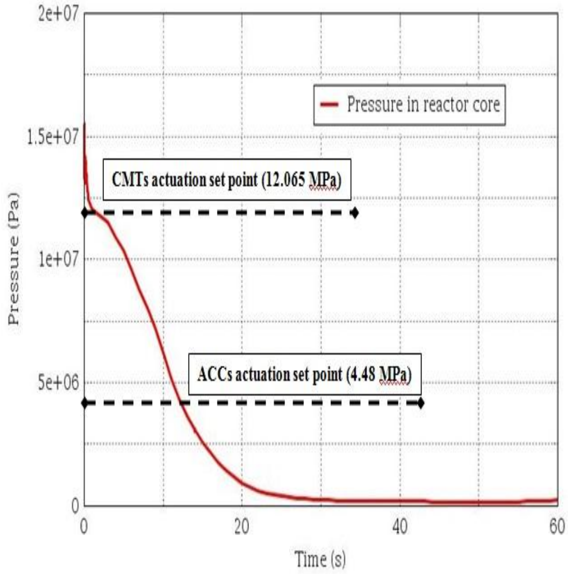


Figure 8: Pressure in reactor core

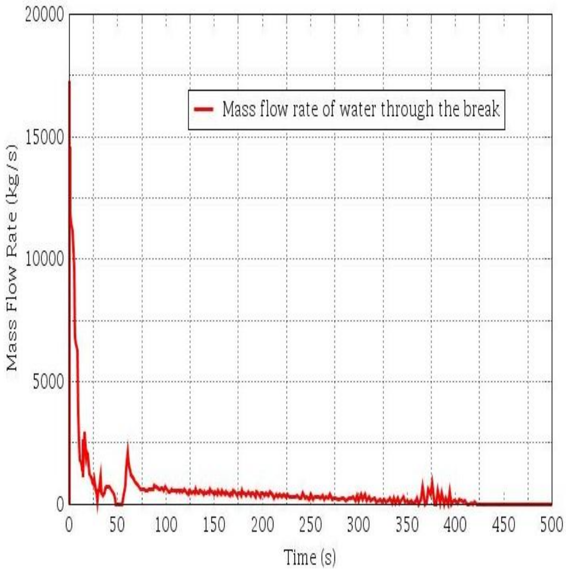


Figure 9: Mass flow rate of water from RCS through break

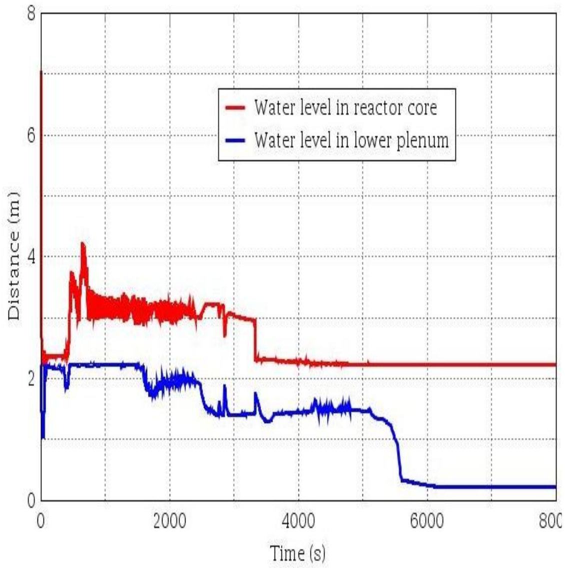


Figure 10: Water level in reactor core and lower plenum

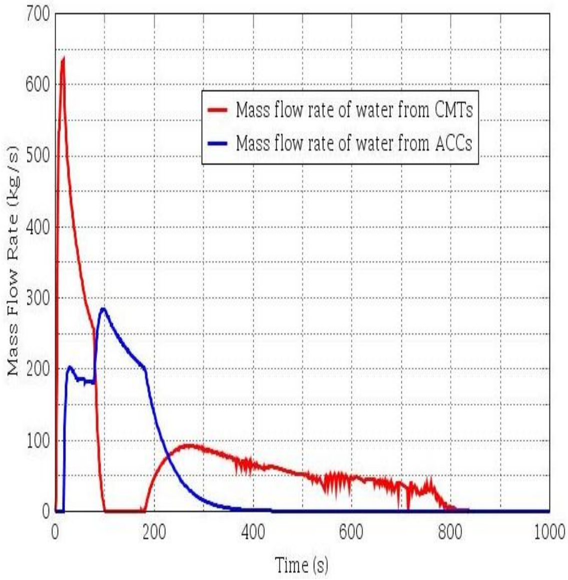


Figure 11: Mass flow rate of water from CMTs and ACCs

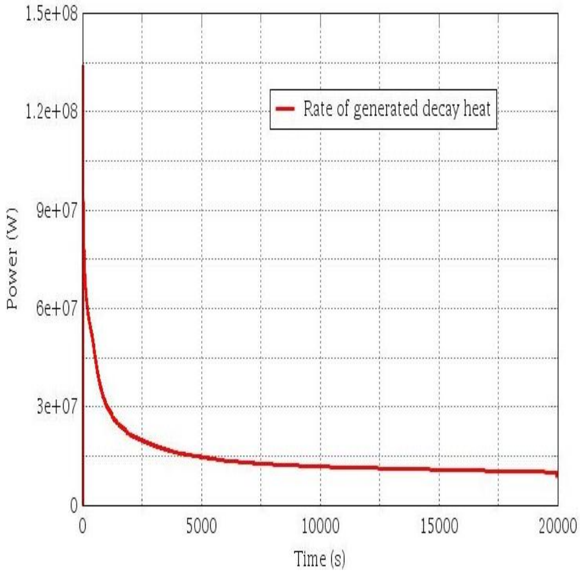


Figure 12: Rate of decay heat generation

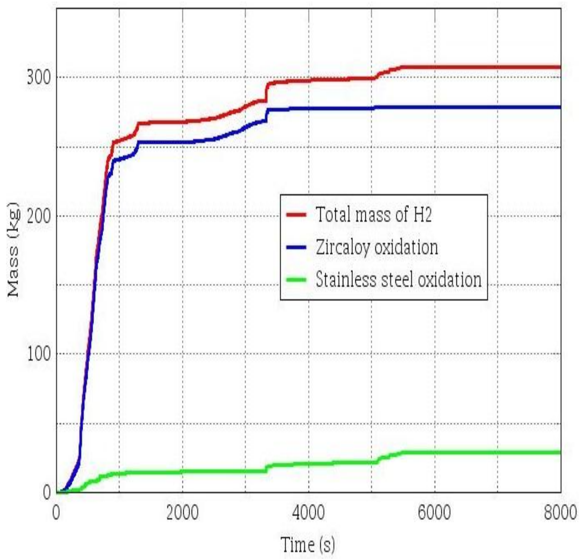


Figure 13: Total mass of generated hydro from oxidations in core

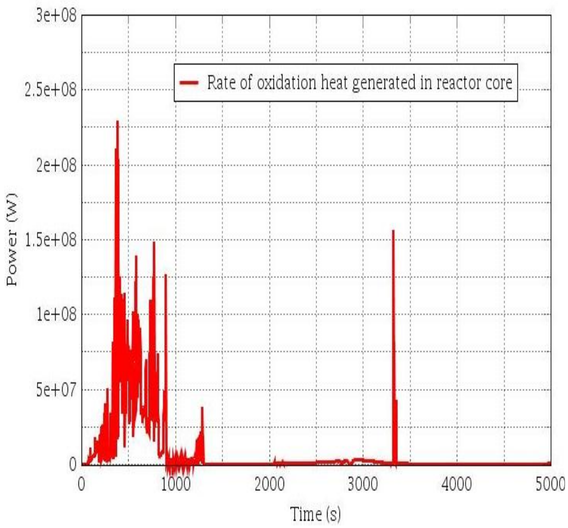


Figure 12: Heat generating rate of oxidation

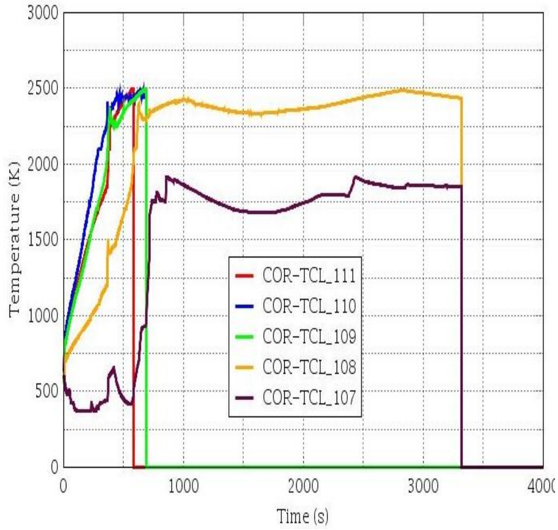


Figure 13: Temperature of cladding in ring 1

Accident progress in lower plenum and external reactor vessel cooling

The failure of core support plate was firstly initiated in ring 1 at 3318.13s. This led mass relocation of debris from reactor core to lower plenum, and mass of debris reached stable state at 15000s (Figure 14). At the time debris relocated to lower plenum, due to of presence of water, temperature of debris decreased at once when water totally evaporated, debris' temperature began increasing and reached to melting temperature (Figure 15). The molten material possibly established some locally unstable melt pools, the largest oxidic pool and metallic pool in lower plenum seen by MELCOR are displayed in Figure 16&17.

When steam temperature in reactor vessel reached to 650^{o}C (923^{o}K) would actuate cavity flooding process, water was injected to flood cavity and reached to demanded height (height of cold leg) after 72 minutes from actuation moment (Figure 20). At the beginning reactor vessel was submerged by water, temperature of lower head was still low and heat exchange process between lower head with water in channel was basically one phase natural convection. When water in lower plenum already evaporated at 6000s (Figure 10), lower head temperature increased due to heat load transferred from hot debris, steam started to establish in channel and the heat transfer between lower head and water in channel strongly happened from 8000s to 16000s when mass flow rate of steam flew out of channel at that time was largest (Figure 19).

Although lower head vessel was externally cooled by water in channel, due to thermal load from hot debris, lower head temperature still increased (Figure 20&21). when water in lower plenum totally evaporated, thermal load inserted to lower head larger, this led heat flux transferred from lower head to water in channel also increased (Figure 22&23).

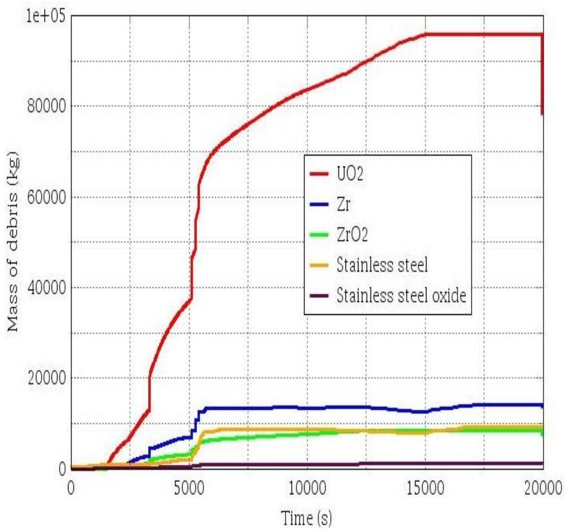


Figure 14: Mass of debris in lower plenum

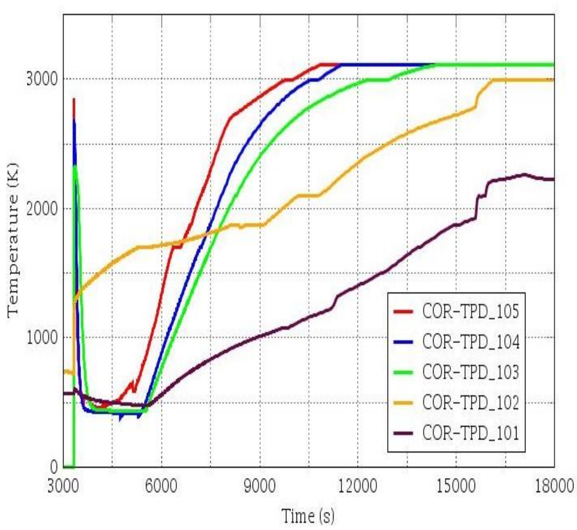


Figure 15: Temperature of debris of ring1 in lower plenum

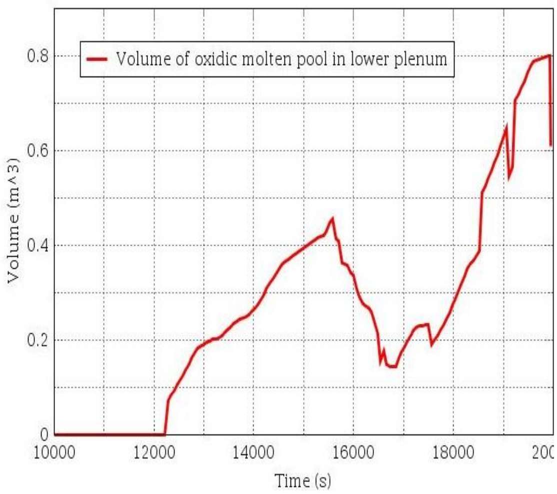


Figure 16: Volume of the oxidic molten pool in lower plenum

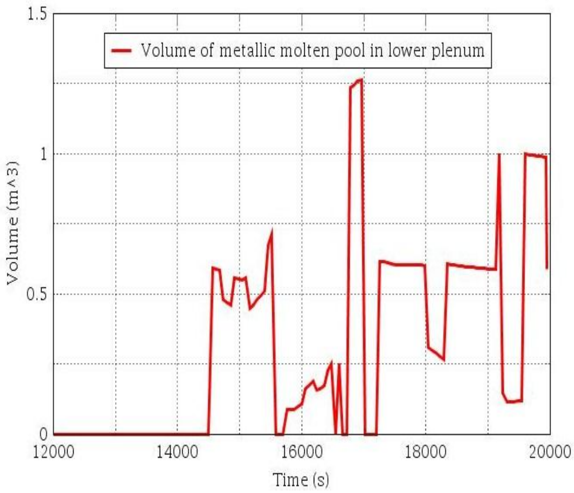


Figure 17: Volume of the metallic molten pool in lower plenum

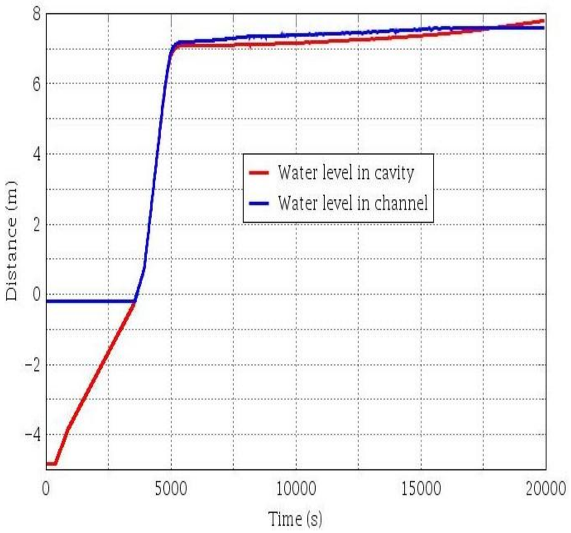


Figure 18: Water level in cavity and channel

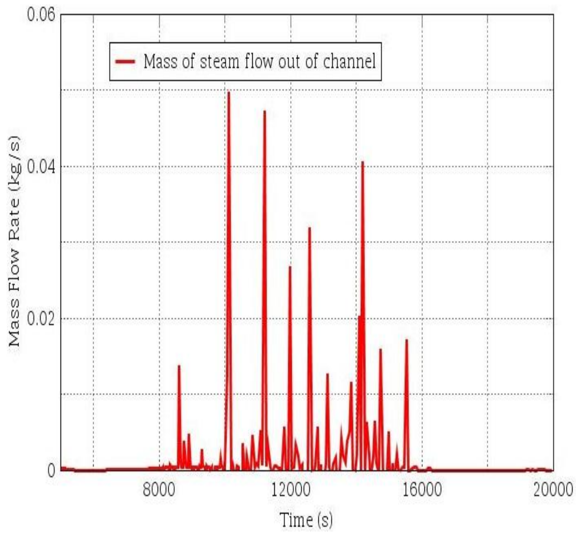


Figure 19: Mass flow rate of steam out of channel

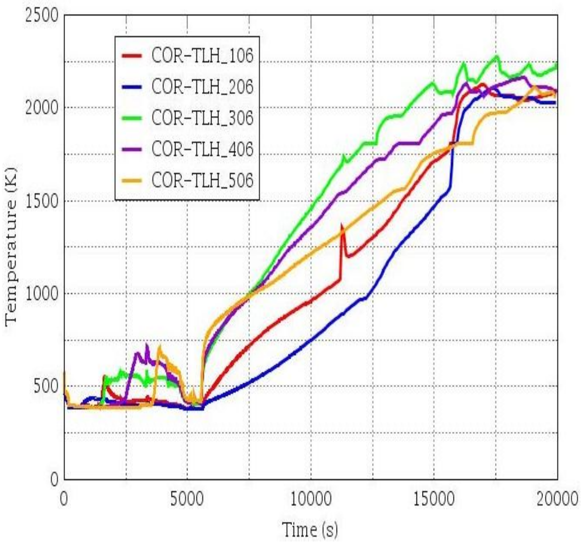


Figure 20: Temperature of segments (1 to 5)

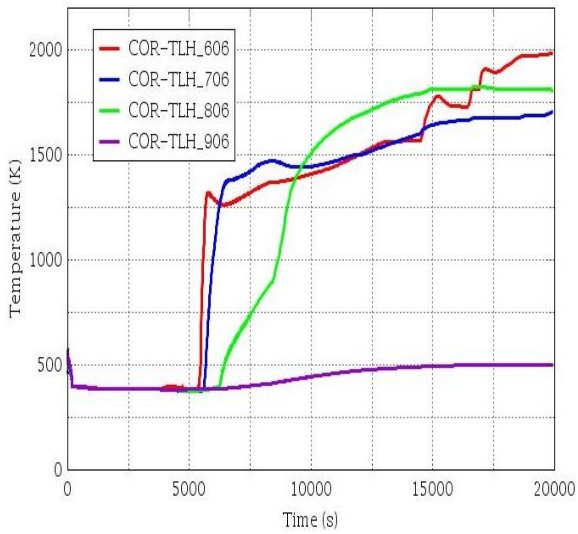


Figure 21: Temperature of segments (6 to 9)

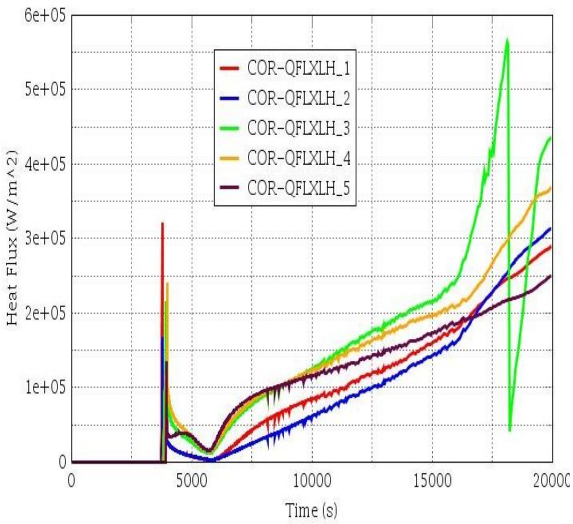


Figure 22: Heat flux transferred from segments (1-5) to water in channel

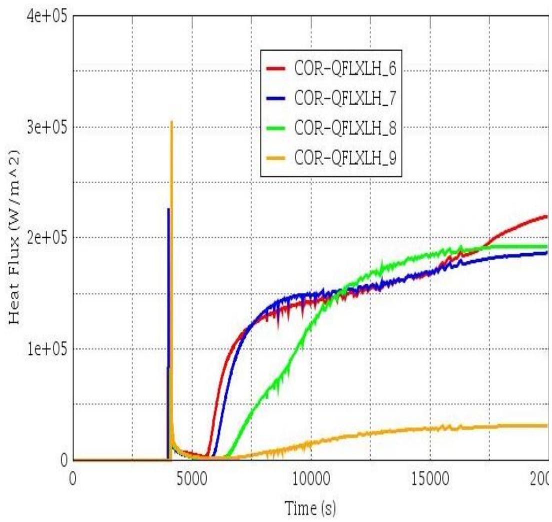


Figure 23: Heat flux transferred from segments (6-9) to water in channel

A local molten pool seemingly established nearby lower head segment 3 of ring 3, this led the segment temperature increased much more than other segments, heat flux transferred from the segment to water in channel was also higher than others (green line in Fig 20). At the 19937.3s the vessel strain in the segment 3 of ring 3 reached to 0.18 which led to lower head failure according to Larson-Miller model.

VII. CONCLUDING REMAKS

The paper analyzed AP1000 in-vessel severe accident progress under flooded cavity condition, the severe accident was initiated by LBLOCA accident which simultaneously happened with SBO accident with additional assumptions that the short term core cooling systems (CMTs and ACCs) was effective, whereas the long term was unavailable, and due to large break therefore the role of ADSs and PRHR are ignored. Under the postulated scenario, the results showed that only availability of short term core cooling systems combined externally reactor vessel cooling could not sustain the integrity of reactor vessel.

As mentioned above, the work done in the paper is a first step in the long term study of IVR strategy. Due to a lot of uncertainties in the study such as: lack of information of structure inside reactor vessel, inlet width of channel or temperature of supplying water to flood cavity… which affected to the result. Therefore this is the preliminary result therefore it did not focus to a specific matter. The results will be updated following up analyses of more precise simulation by MELCOR, and of core behavior using CFD tool (FLUENT) combined with PECM for more precise estimation of thermal load to lower head vessel in the future.

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PHÂN TÍCH DIỄN BIẾN SỰ CỐ NGHIÊM TRỌNG TRONG LÒ PHẢN ỨNG AP1000 DƯỚI ĐIỀU KIỆN LÀM NGẬP HẦM LÒ PHẢN ỨNG

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Giới thiệu: Công nghệ lò AP1000 là công nghệ lò phản ứng nước áp lực tiên tiến của Westinghouse. Đặc trưng thiết kế của công nghệ lò này là các hệ thống an toàn thụ động, hoạt động dựa trên các nguyên lý tự nhiên như trọng lực và đối lưu tự nhiên để đảm bảo tính an toàn của nhà máy khi xảy ra sự cố mà không cần đến sự can thiệp của nhân viên vận hành, có thể kể đến ở đây như hệ thống giảm áp tự động (automatic depressurization system), các bình cấp nước làm mát vùng hoạt khẩn cấp (core makup tanks, accumulators), hệ thống tải nhiệt dư thụ động (residual heat removal system), biện pháp giữ nhiên vật liệu nóng chảy bên trong lò phản ứng (in-vessel retention) thông qua việc làm ngập hầm lò phản ứng…

Bài báo này sẽ tiến hành phân tích diễn biến sự cố diễn ra bên trong lò phản ứng AP1000 dưới điều kiện hầm lò được làm ngập, bằng chương trình MELCOR 1.8.6. Kịch bản sự cố được lựa chọn ở đây là một trong các kịch bản bảo thủ nhất mà có thể xảy ra ,đó là sự cố mất chất tải nhiệt do đường ống lạnh bị vỡ đôi (large break loss of coolant accident) xảy ra đồng thời với sự cố mất hoàn toàn nguồn điện (station blackout) kết hợp với các giả thiết như chức năng làm mát vùng hoạt trong thời gian ngắn (short term cooling) phát huy hiệu quả và chức năng làm mát lâu dài (long term cooling) của bể chứa nước thay đảo nhiên liệu trong tòa nhà không phát huy tác dụng.

Từ khóa: *AP1000, IVR, MELCOR1.8.6, sự cố nghiêm trọng, làm ngập hầm lò.*